

WHERE IS PHOTONICS GOING?: REFLECTIONS UNDER THE SUN

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Abstract

After a short personal view of the first years of the Photonics in Spain, some references about its present situation are given. As a possible future, the first steps towards a Photonics based on the study of the employed mechanisms in the visual system of the living beings are presented.

1.1. A brief prologue

One of the few privileges remaining to those writing the first chapter of a book, or giving the opening speech of a conference, is that nobody expects anything specific in what they are going to read or hear. In the majority of cases the words act only as an introduction and it is assumed that the interesting part will come later. Normally it is a summary of things which everyone knows by way of revision of ideas.

This is the situation in which I find myself today. What I am going to write will only be a set of memories of the past and a series of dreams of what might happen in the next future. Nothing more.

1.2. Introduction

The summer wants to be a time for forgetting. For this it is said that, while it passes, one tries to forget what has happened in the last months and, once the last week is over, to forget what happened then. But this is nearly always false. In the first few days one thinks about the unsolved problems that have been occurring in the last days, and once the summer zenith is crossed, these problems return to mind with the certainty that they will have to be solved when one returns to the routine.

For this, more than for forgetting it is a time for reflection, for letting ideas stew without ties or pressures. Its time to remember past years and plan the coming ones. It is time to think about what might have been but has not, and to dream about what one wants but what may never happen.

Those who already have a certain history behind them, take advantage of these moments which the summer provides to attempt a synthesis of the past. With this we try to make out what might await us in the next few years although we know full well, precisely because of our experience, that we will probably be wrong. For a while, in the same way as I said before that the unsolved problems

haunt the first days of the holidays, we try to look at the past remembering how the years and months passed and how through them we became what we are now. Later, after the first weeks, with the remaining sediment, we forged an fictitious idea of what tomorrow may be like.

Something like this is what I am going to try to do with Photonics: recall first something of what it was, when the word Photonics had still not been created, and afterwards, with these lived and recorded experiences, do an experiment of predicting what it might be like in the future.

1.3. Some personal history

It is not my intention to present a history, more or less exhaustive, of the many ways, applications and views that Photonics has had since the invention of the laser. There are already many articles and books describing it, even written by its creators. As the goal of these lines is not this past story but the possible future, to do so would be to exceed the initial intention. It might be convenient to recall one thing: that everything began nearly forty years ago. That at that time the Second World War began to be overcome and that the first wave of tourists began to come to our country. That the “SEAT 600” was the car which the majority of Spanish families dreamt of and the “Dúo Dinámico” were top of the charts and they were the kings of what was then called “guateques” (parties held normally at private homes, when the parents were out of town). The Second World War and the “600” are basic elements of today’s museums. The tourists are still coming to Spain, but the majority of the children of the average Spanish family are also tourists with the excuse of learning English. And the members of that “Dúo Dinámico” are now producers of other singers although, like the grandfathers recounting the

battles of their wars, from time to time going on stage to remind us that they still exist. Despite all this, there are still many people who go on saying that the laser and optical interconnection, holography and non linear optics, are something of the future. It is obvious that it is a field that will have an undeniable importance in the coming years, it is possible that tomorrow it may be unknown in some areas, but this tomorrow is no more unknown than that of microelectronics, that of the computers or, even, fields as well established as that of machine tools or that of cereal cultivation. I will continue further on.

I do not think anyone would doubt that the birth of the laser brought about the initiation of Photonics. At the beginning of the sixties rumours about the invention of a new system capable of generating a beam of light so powerful that it could cut any type of material arrived to Spain. The press of the time baptised it with the name “Death Ray”. The memory of galactic wars in the comics of those years gave it a semblance of familiarity which surprised nobody. It appeared that, in a practical way, it had been achieved what the children had been reading about for many years. The name “death ray” remained the battle cry of the media for many years after.

I remember giving a talk at the end of the seventies in a University Hall about what the laser was and what tasks it was of use in. Below the title, that I do not remember now, to my great disgust, they had added the aforementioned name. I protested, but they justified the title saying that if it did not appear nobody would go. Fortunately the mortifying concept has disappeared from the press notes although the word “ray” has not. The first day of class, each year, I warn my students seriously that whoever writes “laser ray” in their exam will have their answers checked “especially thoroughly”. Later, as is logical, I do not do so. Despite this, occasional students still continue writing “laser ray”.

The first adventure with the laser in Spain took place in the E.T.S.I. Telecomunicación in Madrid (Higher Technical Engineering School of Telecommunications), the only one of its kind then. The today professor Luque started his doctoral thesis in this topic and, with a group of students of the last years, took on the task of constructing a ruby laser. Without going into detail about its final characteristics, and only mentioning that in some moments several pulses of significant power were achieved (I could not say were or were not laser), I wish to recall two things.

The first one is that what most impressed us of all the laser were some uncommonly big condensers, more than a metre high, for the power supply. They had been made specially by the then Nuclear Energy Commission, formerly JEN, now CIEMAT, and when that venture finished they were sitting in the passages of the school without anybody knowing what to do with those unwieldy pieces of useless furniture. I even remember that somebody commented that the Nuclear Energy Commission was never paid for them. I do not know what has become of them. They will probably ended up in a scrapyard sold by weight. Or will still be in the boiler room of the Telecommunications School in Madrid. I do not know, although I think it would be interesting to know where they are and what has happened to them. The second is that I am sure that all of us involved in that struggle had a clear idea about the possible use of that laser or, in general, a laser. It was obvious that it could burn paper and that, certainly, it could cut any type of material. But nothing more. It was 1967 and optical communications was still a long way from being a reality.

The now Prf. Luque changed his field of scientific interest, retreating into the incipient field of integrated circuits, and some of us who played with him set off on completely different projects. In my case, I crossed the ocean intending to start out on the adventure of ele-

mental particles and accelerators, as fashionable then as it is now. I arrived in Colorado and, after some weeks, the tutor who had been assigned to me, after examining my curriculum, said that he did not think I was cut out for High Energy Physics (as it is now called. Then it had other names which I will not detail here). That my record was much more suited to wandering between Applied Physics and Engineering than where I wanted to enter. He directed me once more to the laser.

At the end of the sixties and beginning of the seventies the two great challenges were to establish a general theory of the laser and to achieve laser effect in the most unlikely materials. I veered towards the first and showed curiosity in the second. I saw how recently sealed CO₂ lasers exploded in the laboratory when made to operate, and other organically coloured ones discharged a thin thread of light whose colour varied, reportedly, at will (the truth is that no change was really appreciable to the human eye). The majority of the great figures of that time, at least the ones who I coincided with in summer courses or in special lectures, were approaching forty and felt they were setting off in a new direction. Haken, Arechi, Scully, Louisell,... were revered names among those trying to start out on this track. None of them, if they are still active, have anything more to do with the laser. At least directly. Although, and this is another fact I will comment on later, the value of what they did then has allowed them to take on new ventures like Synergenics or nonlinear phenomena with communication applications or optical communications. The laser remained, as was said then, a solution of the search for a problem. The field in which the laser was the main player was still not called Photonics but had a series of names depending on who was using it. For some it was Quantum Electronics and for others Quantum Optics. In any case it was always closer to the Physics area than to the technology area.

At the beginning of the seventies I returned to Spain, like many others, without what to do with what I had seen, heard and read.

The applications of the laser were still not very clear. In the field of communications, an environment in which for the obvious reasons of the place where I had landed, The Higher Technical School of Telecommunications, I had to do something, I only had knowledge of a few experiences with signal transmission by air and that with modulators outside the laser cavity the transmission of information could be achieved. However, to think that this could be of interest to the telephonic communications committee was rather absurd. So I decided to look for other clearer areas. Moreover it appeared to fit in with something that was being done in the school, which was the aforementioned attempts to make integrated circuits, which was a mixture of spectroscopy non-linear optics. The former to help to determine structures and compositions of the layers that were grown. The latter, because what I had seen of second harmonic generation was esthetically attractive: to make a red beam transform into a green one after passing through a crystal had an artistic component which I could not resist.

The truth is that, after getting a splendid Jarrell-Ash spectrometer and a 50mw He-Ne laser, spectroscopy no longer interested me and non-linear optics could not be done with the available conventional materials, using the available conventional instruments. I then had to look for new lines of research. Fortunately, the spectrometer, one of the few in the world of its characteristics, is being used nowadays by Prof. Muñoz Merino's group in optoelectronic topics and the laser was used to some doctoral theses which I will comment on later. The purchase was not sterile at least, like others which are commonly squandered in some Spanish universities.

The two paths I followed then were

Holography and the optical properties of liquid crystals. The justification, an excuse really, that led me to these two topics was the possibility of optical signal filtering, using Fourier techniques, in the first case, and in the second, the strong anisotropy displayed and the non-linear effects which were attributed to them in the articles of the time. The reality, at least that which motivated me, was far from that. I chose holography because it was possible to do something which had not been done in my environment, to carry out a stereoscopic film someday. The forecasters predicted it before the end of the decade. I chose liquid crystals, apart from the reasons I have already mentioned, because a cholesteric film that I had bought in San Francisco, in a hippie shop, which some brilliant colours depending on the temperature of the hand that held it.

I remember, and some others still remember, the first holography which I carried out was holding the holographic plate on the door of my laboratory with isolating tape, in the dark. No special table or control equipment was employed. As a matter of fact, it was not available to me. It was a simple Gabor hologram, with a long champagne glass and a small fat wine glass. After developing it and trying to distinguish the 3D image for five minutes, the contemplation of the glasses was one of the most outstanding experiences which happened in the Department then. I think it was 1973 and nothing similar had been seen in those surroundings. There was a form of peregrination, of the most varied kind, to the laboratory in order to see "the photo of the glasses in three dimensions". I continued working in this area for some time, but by 1975, I had decided that the practical results were scarce and the value of this type of holography was merely spectacular and no so much artistic. Because this, I went back to my old paintbrushes and oils, and say goodbye to the laser and Kodak or Agfa plates.

The consequence was that in my incipient group we started to dedicate ourselves intensely to liquid crystals. The first thesis to be presented, in 1979, studied the magneto-optic effects in optical guides with MBBA. The armature of a simple electromechanical relay acted as a variable magnetic field and a solar cell acted as a detector. It could not be said that the instruments needed were very complex. The thesis was very fruitful: besides being the first in this field, its author is today, and has been for various years, General Director of Foreign Trade.

I am not going to continue with the rest of the story, apart from not being the purpose of these pages, because some of the main characters are the authors of the following pages. They carry on today with what I started in the seventies, with more drive and greater success, and with clearer ideas and more specific objectives, than I had when I started. However, I would like to emphasise two aspects which I feel to be fundamental.

The first is that when someone wants to do something, they can always start independently of the available means. What one has to know is what can be started with possibilities of achieving reasonable success. To try to work with solitons, for example, would be absurd if one does not have the suitable means. It would be equivalent to trying to do the work I tried to do at the beginning of my career, non-linear optics with solid crystals. It is necessary to look for objectives in accordance with the available means. It is always possible to find original work if one is ingenious and looks, in drawers and wastepaper baskets, for something that might be useful for achieving what one has proposed to do.

In this respect I can remember something I have just read which is related to the recent death of the Nobel Prize winner, Ernest T.S. Walton who, with Cockcroft, received the award for being the first to split the atom, in 1932, while they were students in Cambridge

University. Their tutor then, Lord Rutherford, seeing the way they had achieved this (with car batteries, bicycle tubes, biscuit tins and glass flasks) said that it was "A million volts in a soapbox".

The second is that to try to follow a line of research through fire and water, if the results are not as expected, is absolutely absurd. It is much better to give up and start again a new line. This may be very arguable and possibly even totally erroneous, but I have always acted in this way. It is very possible that many of the great discoveries would never have been made if this advice had been taken, but through my entire professional life, more or less, I have followed this adage. Thanks, possibly to this, each of the groups which were formed from the initial nucleus of the seventies, has been able to follow different trajectories, because they have been those that I began with them and later gradually abandoned. It is a way, like any other, of having a garden with many crops rather than a single crop plantation.

1.4. What is happening today?

The following authors will give a more precise account of what is happening today in the many branches of Photonics than I could give here. For this reason I will offer only a very general view of how I see some of the more interesting topics and how I think they will evolve. I will also comment on how the actual situation has developed, because from this many conclusions can be derived.

As is only logical, I will not refer to the whole area of Photonics. It would be too ambitious to try to cover in a few brief pages. Some years ago, in November 1989 to be precise, I published an article in which I analysed the situation of Photonics at the time. In it I included a table which attempted to show what Photonics covered then. It was like that in Figure 1.1.

As can be seen, only giving a few details of each of the captions would take much more time and space than I have been assigned. For this reason I will limit myself, almost exclusively, to the part of Photonics which is most interesting to those who may read these sentences and who, I presume, are interested in Optical Communications. However, to do this, I must approach another field which in principle seems unrelated, but as we will see, it is now intimately related to its evolution. I am talking about Optical Computing.

There was a strong dichotomy between Computing and Optical Communication. The former was essentially of interest to investigators from the world of Physics and the latter to those of Engineering backgrounds. It was around the late seventies or early eighties and the basic interest of the field of Optical Computing was the appearance of bistable optical devices that could apparently work under conditions of higher velocity and lower power than their electronic equivalents. The big laboratories of the U.S.A. and Europe initiated a great race. The reality after a few years was different. The performance of the electronic computers got better and better

and the requirements of their competitors, optical ones, remained incompatible with routine use.

However, a link between the two appeared, which was strongly exploited by communications. It is synthesised in Figure 1.2.

On one hand there are the limitations in the transmission of data which had been solved in the optical communications thanks to optical fibres. On the other hand, in computation, the velocity limitation for commutation between two states had been reduced due to the advent of optical stability. There was a bottleneck between the two limitations which was that of the interconnections and the packaging of their elements. In the same way as this bottleneck was common to both, at the end of the eighties it was concluded that what had been thought of as a solution for computers, that is the commutation velocity, could also be valid for communications, applied to the field of circuit or packet commutation. Thus, photonic switching was born, one of the most active branches of optical communications in the last few years.

Here it is convenient to stop and comment on the solution which has been adopted in this

area, which is in my opinion the most pragmatic that could be taken. Ideally, to achieve real optical communications the elements making up the system should be governed by photonic or optical concepts only. In other words, in photonic switching, for example, there should be exclusively optical devices with no type of electronic addition. This is something which will possibly be achieved someday, although until that time comes, how should we

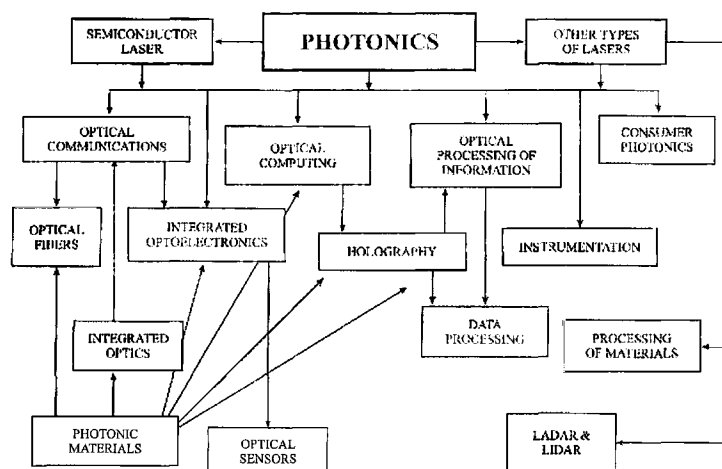


Fig. 1.1. General scheme of the different areas covered by Photonics

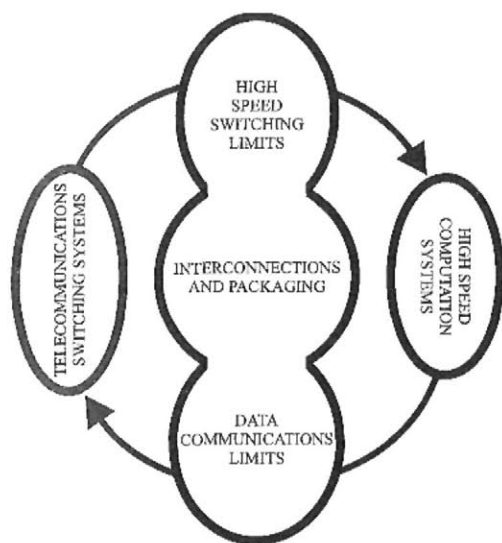


Fig. 1.2. Relation between Optical Computing and Optical Communications concerning their main limits and advantages.

proceed? Should we keep on trying out purely optical systems until the desired one is obtained? Or would it not be more convenient to mix optical and electronic concepts, taking the most useful parts of each? As is logical this course of action has been followed. The photonic switching systems which are presented in conferences and appear in technical journals are really hybrid systems, a mixture of truly photonic components, like SEEDs, and other electronic ones which carry out diverse functions. Pragmatism, as nearly always, has predominated over idealism.

Another topic which has been stimulated by Optical Computing is that of interconnections. In Figure 1.3 there is a brief summary of the different levels that can be shown in this area.

As can be seen, these vary from the massive connections between systems to those at the chip itself. This figure first appeared in articles related to computation and to a certain extent, is related to another that we will see

later in the case of Neurophysiology. To solve these cases the optical fibres themselves were used as a starting point in the case of systems, and more complex solutions were found derived from holographic concepts, for interconnections between plaques or chips. These solutions, without going into detail, have been adopted in Optical Communication for the commutation systems. Once again, topics developed in one area are used in another, before being used in their original area.

Another field which should also be mentioned here is related to the transmission of solitons and can be expected in the coming years. However, the subsequent chapters deal with this in greater detail, so it would be absurd to start here.

1.5. Lets talk about the future

Any preview of the future always has a personal touch. Present realities are mixed with possible projections of the coming years, with the desire that what we foresee moves

OPTICAL INTERCONNECTION

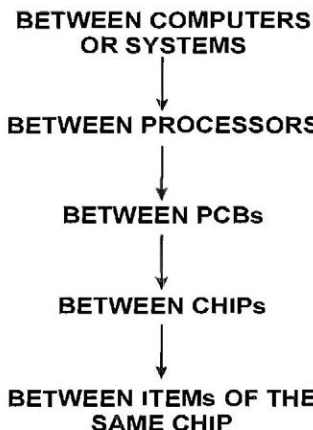


Fig. 1.3. Different levels of optical interconnections.

towards our wants. Wants which, on the other hand, can change quickly from day to day.

Something of which there is no possible doubt is that the next few years will see a notable increase of fields in which photons will occupy the site now occupied by electrons. Although this seems sure, something I am not so sure about is that photons will displace electrons in some fields in which the forecasts suggest they will. What I have said about electrons could be true for radiofrequency waves or certain forms of image recognition, for example.

One of the most fundamental characteristics that is going to determine the development of Science and Technology in the next years, years in which the next millenary will commence, is the absolute mixture of techniques and knowledge bodies. If up to now, the introduction of new technology has brought about the inexorable demise of the previous one, in the next stage it will be the harmonisation of all the existing and integral exploitation which will determine progress. There are many reasons for this. In fact we are checking the truth of the above in many techniques, for example, in optical communications. I will mention this again later on.

The fact that I consider essential for the next decades is the displacement of the interest of Science and Technology from Physics related areas to Biology related fields. What I say here I might be better not to mention, or to say in another way, bearing in mind that Photonics is a field born from the development of Optics, Electromagnetism and Materials Science and that, according to what I said above, it should really be in decline. However I will attempt to show, in the following pages, its displacement towards the Biology related areas will determine a new activity that could make it even more significant.

I have shown, in the last section, that the areas where Photonics is active are nearly all fields in which modern development is flour-

ishing. However the philosophical approach has been more of achievement of long desired goals, and attempts achieved with other techniques, than to reach self imposed objectives not foreseen with old or new technology. At the same time, and derived from all of them, a great deal of the actual working methodologies in Photonics are a consequence of analogous ones used in fields like Electronics, conventional Communications or digital Computers. I believe that Photonics should develop its own line of research and that this should be different to other technologies.

This is where I want to centre my interest from now on. It is clear what path Photonics will follow in the conventional areas. Now we must see what new paths can be followed with Photonics. Continuing with what I explained a few paragraphs before, one of them should be related to the explosion of interest towards Biology which will occur in the coming years.

The first solution which would be easy to adopt is to say that the applications of Photonics in conjunction with Biology would be, for example, the treatment of organic tissues or transmission of medical images using optical communications. However this means going back to the conventional fields. Surgery using laser have been habitual topics since the mid-seventies and the transmission of images is a simple application of wide band communications. There is nothing which supposes a dramatic change in the methodology. It is not a paradigm in the sense of T.S. Khun, but the evolution of technology in the sense of G. Basalla.

To attempt to find a clue about this paradigm, the best course of action is to localise what part of Biology, or branch, is directly related to Photonics, from an operational point of view. This part is, of course, the visual system of the living beings, more specifically, the vertebrates. Both areas are related to photons and, in accordance with the well known definition of Photonics, the visual system of the

vertebrates "*detects, guides, amplifies, modulates and modifies the characteristics of optical radiation, with the aim of processing the information*".

There is another fact I consider basic to the study of the visual system¹: approximately 60% of all perceived sensorial information comes through this system. Moreover, nearly 50% of the cerebral cortex is destined to process the information received in this way. It is obvious that it is interesting to know how this processing works. The performance of the visual system of the vertebrates is much more efficient than any artificial system created by man. It is useful to make some comparisons between how animals process the information they perceive and how it is carried out in artificial systems.

Most digital equipment dedicated to the processing of visual information is based on the conversion of signals into symbols using algorithms, of greater or lesser complexity, with a very strong software base. Its efficiency is quite poor because of the huge computational power necessary to process and extract information from any image which varies with time, like those that surround us. For example, with a conventional image of about 750,000 pixels, which varies at a conventional velocity of thirty images per second, if we wish to extract just one instruction per pixel, a computer capable of carrying out 23 million instructions per second would be needed. In the real case, where there is more than one instruction per pixel it would necessitate faster and faster processors.

On the contrary, the visual system of the mammals is capable of recognising image changes which last between 70 and 200 milliseconds. Curiously, this is achieved using neurons which are not much faster than some

of the electronic circuits available on the market: whose response velocity is about 2 milliseconds. On the other hand, in the artificial image processing systems, any sequential algorithm implemented in a conventional digital computer, requires millions of operations, while in the biological systems there are no more than 46 stages in the signal transformation. In other words, the performance in each stage of processing is millions of times better in animals than in the man made machines.

There is another fact I would like to highlight. It is the comparative difference between the space necessary for the processor system of a conventional computer and a mammal. In mammals the space is limited by purely biological characteristics, namely the reproductive system. The size of the head is limited by the volume of the pelvic cavity. This means that the length of the "cables", a basic element of the nervous system, can not be indefinitely elongated. This is achieved by making the performance and efficiency as high as possible. To give specific details it is necessary to start with the approximate length of conduction in the human brain which is about 108 m, while the volume of the human cranium is rarely more than 1.5 litres. One of the strategies adopted to economise cabling is to group processing units in such a way that neighbouring structures process similar representations. The other is to share these conductions, in such a way that one axon can be used for codifying a large number of different codifications.

Finally, to highlight even more the performance of the brain compared to artificial information processing systems, it must be said that a neuron uses only 10^{-15} joules of energy per operation, while the most efficient silicon can get down to 10^{-7} joules, at best. Thus it

¹. Part of the following text has been published in the paper 'Una aproximación hacia un nuevo paradigma: la mimesis biológica', from J.A. Martín Pereda and A. González-Marcos, Mundo electrónico, Sep. 1995.

can be said that is seven or eight orders of magnitude more efficient in terms of energy consumption. Thanks to this, and other factors, the brain can reach much higher processing velocities than modern computers. One of the most modern computers can reach 10^9 operations per second, while the brain, even in repose, can reach 10^{11} . And this is so, even taking into account that the neuron is a really slow element compared to the modern integrated devices: 10^{-9} sec. for these, compared to 10^{-3} sec. for neurons.

It is therefore obvious that to understand the brain's processing mechanisms, and specifically those of visual information, could be a much more fruitful task than to continue to create artificial machines based on non-biological processes.

The method I will propose here, in fact, has two branches and these two define the two possible approaches for exploiting the bi-

ological solutions to solve problems. The first has to do with how the light incising on the photoreceptors of the retina produces a much more efficient signal than that of the conventional semiconductor devices. The second refers to the neuronal architectures in the brain which give rise to the complex process of vision. I will dedicate the rest of the chapter to giving some brief details of these two ideas.

1.5.1. Process of light reception in the retina of mammals [1]-[6].

What makes the retina such an interesting field of study, is its relatively simple configuration and the great complexity of the operations it is capable of carrying out. The simplicity is derived from the fact that there are fundamentally only five types of cell in its architecture. The complexity comes from the enormous variety of processes that it carries

out, from object recognition and detection of movement, to differentiation of colours and distances. It is certain that a large number of these processes are interpreted in the cortex and that it is, in fact, here that the sensations which we perceive are produced. However, without the signals that the retina produces, the cortex would be like the main core of a computer with no external input connections.

The study of the retina, which can be as complex or as simple as one wants, offers some undeniable advantages with respect to other sensory systems. In fact, some of them have structural configurations, which are in a way equivalent. This is the case for the olfactory system, although

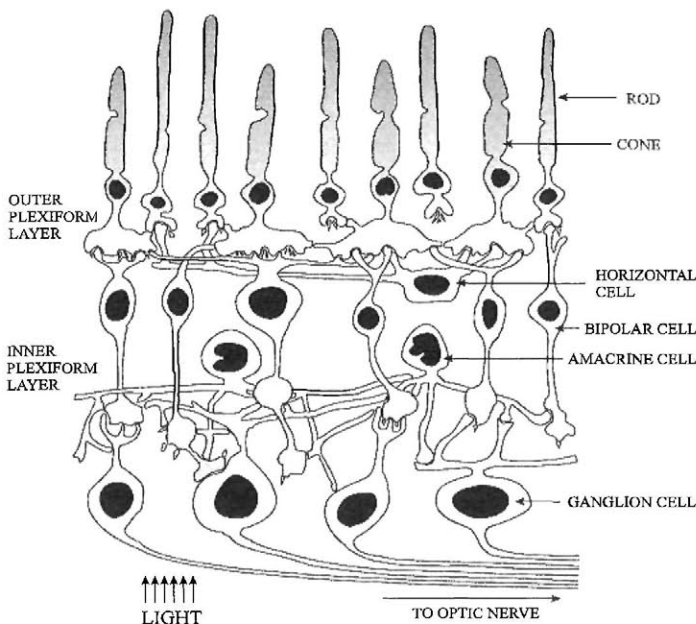


Fig. 1.4. Retinal neurones and their connections: simplified representation of section of primate retina, showing rods and cones with their pedicles forming synapses with horizontal cells and bipolars. The later connect with amacrine cells and ganglion cells whose axons form the optics nerve.

with a less complex response. Consequently it could be said that once the function of the retina is understood, the conclusions are equally applicable to many other areas.

The first morphological description of the retina was established, in a clear and unambiguous way, by Cajal, and remains the basic configuration. Some new paths for circulation of nerve impulses and certain feed loops have been discovered since then but the five elemental types of cell which make it up and the sequence of phenomena between them remain the same. The basic configuration of a small section of the retina is shown in Figure 1.4.

The light, which reaches the photoreceptors after passing through the anterior layers of cells, is transformed by them in a strong depolarisation. This signal is transferred to the bipolar cells, with interactions mediated through horizontal cells. The signal from the bipolars finally passes to the ganglions, again by direct synaptic connection or by means of the layer of amacrine cells between the two. The

resultant signal enters the optic nerve to go into the brain. The previously mentioned set of cells forms a set of layers whose extremities are the layer of photoreceptors and the ganglions.

It seems necessary to make some comments on the above. Some about the function of the photoreceptors and the others about the function of the rest of the retina. The first are important because of their mechanism for transforming light into electrical potential. The second for the way in which they process the received electrical signal in such a way that it can be recognised and interpreted by the brain. According to the previous strategy, we will firstly see the light reception process and then the architecture. However, with the objective of revising some concepts which might have been lost in the memory, I will give a brief summary of how the process of conduction works in the animals, with special emphasis on the mammals, since it will be fundamental later when we apply it to their retina.

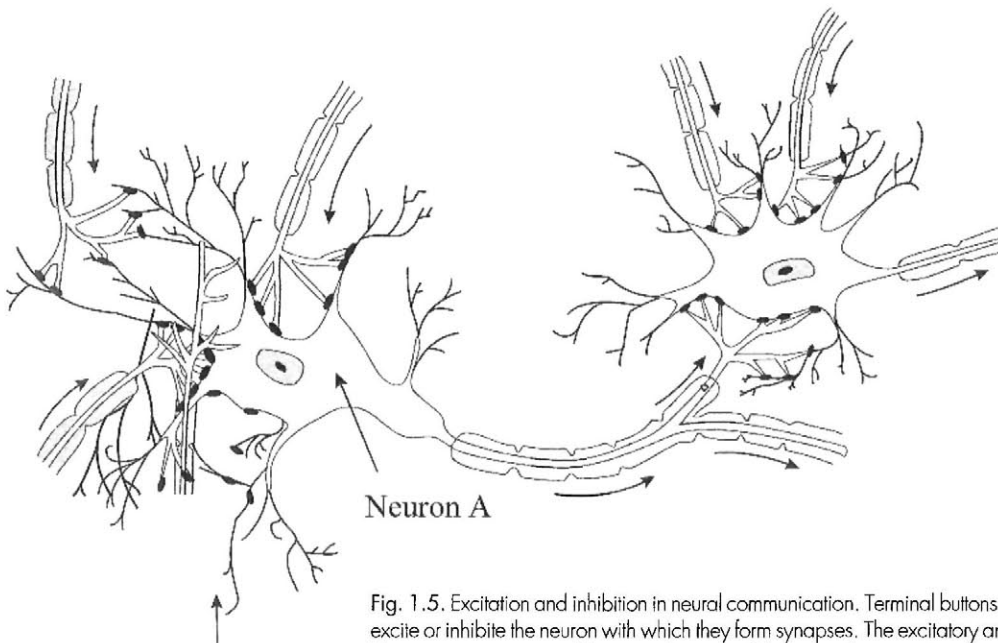


Fig. 1.5. Excitation and inhibition in neural communication. Terminal buttons may excite or inhibit the neuron with which they form synapses. The excitatory and inhibitory messages control the rate of activity of the axon of neuron A.

1.5.1.1. Basic ideas of neuronal behaviour

The structure of the neuron, which has been known since last century, is shown in Figure 1.5. The essential parts are schematically summarised below.

(a) The *soma*, cell body, is the part of the neuron which contains the nucleus. It is the focus of the cellular process, in which the dendrite and axial processes originate and terminate. Although a large number of dendrites may arrive, each cell has, at most, only one axon. The majority of the neuron's intracellular organelles are contained in the soma.

(b) The *cell membrane*, which is composed of two layers of lipids between which there are proteins necessary for the majority of the active processes. Some of these proteins form channels for the entrance and exit of ions, while others retain certain compounds which can be liberated depending on the situation and others act as ion pumps, making these enter or exit, independently of the electrochemical gradient that may exist inside and outside the cell.

(c) The *dendrites*, or elements which transmit the soma signal to the outside or from the exterior to this. They are profusely branched and the form they adopt may depend to a great extent on the type of cell considered.

(d) The *axon* is the channel which usually guides the nervous impulses from the soma to the nerve endings and the synapses. In the case of the sensorial neurons the axon carries signals in both directions. Its diameter is proportional to the cell size and does not normally vary along its whole length.

(e) The *synapses* are the terminals through which cells contact each other. They are made up of a presynaptic terminal and a synaptic cleft which separates the presynaptic nervous membrane from the postsynaptic equivalent. A limited number of synapses do

not have these characteristics but a small resistive union through which the nervous impulses pass. These synapses are denominated electric as opposed to the ones with a cleft which are denominated chemical.

Other parts of the neurons, like the intracellular organelles, the Nissl matter, the neurofibrils, the myelin or the Schwann cells, although important in the overall behaviour of the neurons, are not important in the processes we will study here.

Of all the neuronal elements mentioned up to now, there are two which are more important from an operative point of view. They deserve special attention and so, we will dedicate some lines to them. They are the ionic canals and the synapses. At the same time, and given the importance that they have in the overall behaviour of the cells we will also indicate some ideas about the action potentials and how they are transmitted by the neurons.

Ionic Canals

They are structures composed of proteins which allow the passage of ions from one side the neuronal membranes to the other. This movement is determined by the electrochemical gradient which exists between the two sides of these membranes, going from greater to lesser concentration. If an electrical gradient appears, this movement can be annulled.

The ionic canals can be open or closed, depending on the voltage in the membrane and can be due to, for example, the presence or absence of action potentials.

Action Potentials.

One of the fundamental characteristics of the nervous system is its capacity to generate and transmit nervous impulses. A nervous impulse which is propagated through an axon is denominated an action potential and it is derived from the activation of the previously mentioned ionic canals, which make a rest

tension of some -80 mV. change to a positive depolarisation of around +40 mV. This depolarisation is followed by a process of repolarisation so the membrane recovers its equilibrium state. The generation of the action potential at one point of the neuron gives rise to the activation of the ionic canals which surround it so that this potential is propagated along its whole length. The conduction takes place in only one direction since the action potential leaves behind an area of inactive membrane. These potentials only meet at the axons and in the final processes of the neurons of the nervous system.

The process for which the potential to which the neuron gets is inferior to the equilibrium, that is, less than -80 mV, is called hyperpolarization and can be produced by a great variety of causes. Among these is the reception of light in the photoreceptors of the retina which will be discussed further on.

Synapses.

The term "synapse" was coined by Sherrington, in 1897, to designate the junction of two neurons. Its basic structure consists of the juxtaposition of the membranes of each neuron in such a way that they form a more or less precise junction, called active zone. This precise character is very important since the width of a synaptic contact is around one micra or less, which enables the maximum degree of interconnection in a minimum of space. Another important property is that this union is orientated, that is, it always goes from a presynaptic process to a postsynaptic one. The last property is related to the way it works, which in chemical synapses, the presynaptic process liberates a transmissive substance that acts on the postsynaptic process. Thus, a synapses converts an electrical presynaptic signal into another chemical one which later changes back to an electrical postsynaptic signal. In this way, its form of behaviour is like that of a non-reciprocal dipole.

In a traditional way, the synapses can be considered simply as a connection which can impose an excitation or an inhibition on a receptor neuron. At the same time, there are different types of synapses. The most usual are divergent, in which there are various exits but only one entrance, convergent, which have the opposite structure; several entrances but only one exit. In parallel with these there are other types of configurations, in which the predominant factor is an inhibition that can be in either a progressive or regressive sense, or a mixture of the two, like in the type denominated recurrent.

The Hodgkin and Huxley equations.

The Hodgkin & Huxley equations were proposed in 1952 and, despite the passing years, they are still the basis of all the proposals that are made in relation to the behaviour of the potentials which are propagated through the neuronal axon and how they behave with time. Although there are other complete models, here we will limit ourselves to the Hodgkin & Huxley original since it provides a more direct view.

The first step of their approach is based on proposing, empirically, the equations which are capable of describing the changes in conductance of the membranes. In the case of potassium this conductance is given by

$$g_K = g_{K \max} n^4$$

where $g_{K \max}$ is a constant equal to the maximum value of g_K . The underlying idea is of this equation is that the potassium ions can pass through the membrane when they move four charged particles to a specific region of the membrane under the influence of an electric field. The quantity n is the probability that these particles are found in the adequate position. Its variation with time is given by

$$\frac{dn}{dt} = \alpha_n(I - n) - \beta_n n$$

where α_n and β_n are time constants which depend on the voltage according to the empirical expressions

$$\alpha_n = \frac{0,01(V+10)}{\exp[(V+10)/10]-1} \quad \beta_n = 0,125 \exp(V/80)$$

In turn, the conductance of sodium is given by

$$g_{Na} = g_{Na\max} m^3 h$$

This new equation is based on the supposition that each sodium canal can open up by movement of three particles, each one having a probability m of being in the right place, and can close by movement of another particle, with a probability $(1-h)$. m and h are given by

$$\frac{dm}{dt} = \alpha_m(1-m) - \beta_m m \quad \frac{dh}{dt} = \alpha_h(1-h) - \beta_h h$$

with

$$\alpha_m = \frac{0,1(V+2,5)}{\exp[(V+25)/10]-1} \quad \beta_m = 4 \exp(V/18)$$

and

$$\alpha_h = 0,07 \exp(V/20) \quad \beta_h = \frac{1}{\exp[(V+20)/10]+1}$$

The total current, I , circulating in the membrane is given, in its simplest form, by the expression

$$I = C_m \frac{dV}{dt} + I_K + I_{Na} = C_m \frac{dV}{dt} + g_K(V - V_K) + g_{Na}(V - V_{Na})$$

being C_m the capacity of the membrane.

If I is known it is possible to obtain V from it, by numerical integration. This has been done for a large number of cases and the results obtained experimentally coincide with those derived from this model.

Levels of the nervous system of the animals and some considerations about the relation Photonics - Biology.

Although it is only to try to make a comparison between what has been said before and the interconnections in photonic systems, in Figure 1.6, the main structural levels in the configuration of the nervous system are shown. As can be seen it embraces everything from the simple molecules and synapses, to the central nervous system, including neurons, neural networks, maps and systems, like the olfactory or visual.

It can be seen that the nervous system covers more than eight orders of magnitude, from the molecular dimensions, measured in Angstrom units, to the nerve fibres, that can

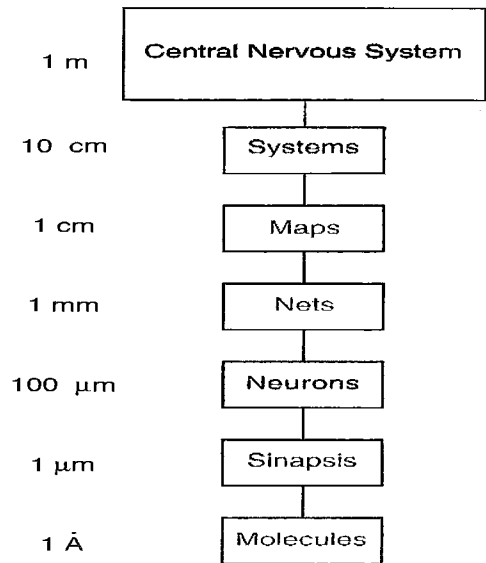


Fig. 1.6. Schematic illustration of levels of organization in the nervous system.

reach up to several centimetres. The parallelism between the two fields seems evident. At the same time, as a first justification of another of the relationships between Photonics and neurophysiology, it is necessary to highlight the future role of optical interconnections. As has already been said, Photonics should not only be limited to carrying out specific functions in particular fields.

Another task which it should also do is to serve as support in understanding other scientific-technical areas which for one reason or another need a model suitable for their methodology. The case of neurophysiology is a clear example.

For obvious reasons getting to know what and how the human thinks is something that for the time being is beyond the reasonable boundaries of modern science. One of the facts which makes progress difficult in this area is, among others as stated by F. Crick in his recent book "The Astonishing Hypothesis" is the impossibility of carrying out experiments on live humans. The only possible way of getting to know some of the secrets that nature keeps is through simulation or mimesis of the architectures developed by nature. It is obvious that an artificial system can never completely emulate a living being and even less get to feel sensations or emotions. However some behaviours can be equivalent to developments carried out following the course dictated by evolution over the centuries. One of those which can contribute most lessons is the study of human neurophysiology.

If one of the goals to be persecuted is to mimic animal behaviour, these goals should try to follow the models by which this behaviour is achieved. If one of the goals is to develop something similar to the brain, the means should in the same way resemble the biological ones as much as possible. In other words, the basis should be more of a physical support ("hardware") than a logical support ("software"). With these premises, and the limita-

tions of electronics, which have already been commented, only using photonic interconnection concepts can the necessary packet densities be reached. Thus an important link arises between Photonics and Biology, far from the conventional application of the laser in treatment of tissue, which is the most common at present.

Although the topic outlined in the previous sentences should be explained in more detail, it seems opportune to leave it now and present a specific case of how living beings function and try to extract the maximum teaching from it. This case, as has been stated before, is the visual system of the vertebrates.

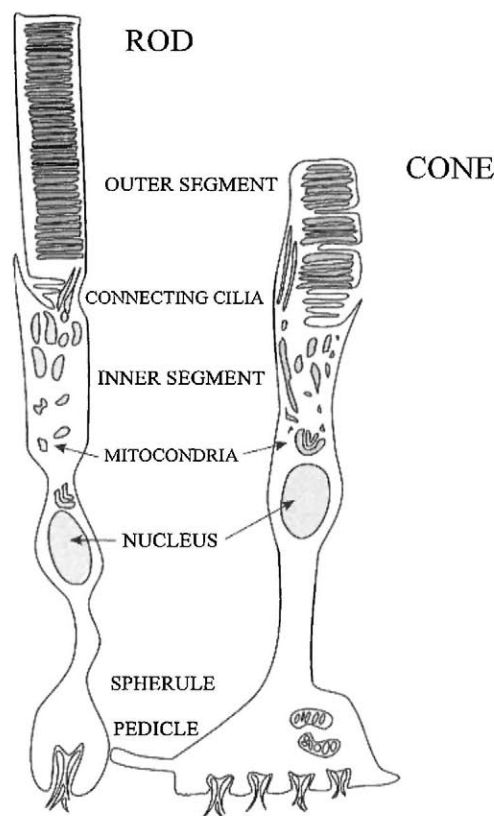


Fig. 1.7. Rod and cone cells of the mammalian retina.

1.5.1.2. Photoreceptors. Light conversion process

The two fundamental types of photoreceptors are the cones and the rods (Fig. 1.7).

Both types of cell are elongated and are composed of an external segment, another internal one, a cellular body, the axon and the synaptic terminal. The vertex of the external segment faces the interior of the eye, that is, towards the position most distant from the entrance of the light. This segment is composed of membranous disks piled perpendicularly to the principal axis of the cell. This part contains the photopigments. While in the rods these are absorbed in disk shaped membranes, without continuity with the external membrane of the cell, in the cones, these molecules are found in the folded membranes which coincide with the cell's. The external segment is connected to the internal one by a narrowing. This narrowing is essentially made up of mitochondria which have no importance in the transduction of light. The axon of both types of cell is short, generally not reaching 50 microns, except in the fovea, where the dense packaging leaves very little space for connecting to the rest of the retinal layers. For this reason, the axons of the cones can reach 500 microns.

Given the different function carried out by cones and rods, rods for night illumination and cones for daytime, their structures are different too. The external segment of the rods is long, between 25 and 50 microns, and fine, between 1 and 1.5 microns. Due to this they can form very dense packets reaching values of 500,000/mm². This high density allows them to capture all available photons. On the contrary, the external segment of the cones is shorter, between 6 and 8 microns, and a bit thicker, between 3 and 5 microns. As a consequence, the cones tend to be distributed less densely, reaching only between 5 and 10 per cent of the density of the rods.

Only in the fovea can the packing density be similar. On the other hand, the axon of the rods is very fine, reaching only 0.25 microns. This is consistent with the slow response of the cells to light. Their synaptic terminals are also of very reduced size. The axon of the cones is thicker, about 1.5 microns, which corresponds with a faster response to light. Their synaptic terminals are also bigger than those of the rods.

Independently of the distinct characteristics of the specific function of the cones and rods, the process of light transduction is very similar in both cases and is rooted in the photopigment associated with the membranes of the external segment of both. If the pigment is analysed in an way isolated from the receptor, its absorption spectra is totally analogous to that of the receptor sensitivity. This photopigment is configured in two essential parts: one *chromophore*, called *retinal*, which is derived from vitamin A, and another protein/oligosaccharide complex, denominated *opsin*. When light incides on the visual pigment of the rods, the rhodopsin, an isomerisation is originated of the retinal that changes from its normal 11-*cis* form to the all-*trans* configuration. After a series of changes in the rhodopsin, with longer or shorter intermediary states, the complete separation of the opsin and the retinal. If this process takes place outside the retina, it brings about the definitive disappearance of the initial photopigment. However, within the retina, it can regenerate itself thanks to a set of enzymes which are present in the cell. Depending on the recuperation time, there will be a greater or lesser possibility of adapting to the external condition. It is for this reason that a shortage of vitamin A can bring about a specific night-blindness, as there is not a sufficient quantity for reuniting with the opsin and recuperating the initial active pigment.

The next stage involves the potentials existing in the cells and how they change with

incident light. As has been commented previously, the potential of the cells is slightly negative compared with the exterior. The situation in the photoreceptors in complete darkness is analogous, but with certain small details which differentiate it from the normal equilibrium. In this case, there is a tension of about -40 mV, quite different to the potassium equilibrium potential, which is -80 mV. This is because of the existence of a darkness current of sodium ions, which penetrates in the external segment through a large number of canals which remain open. The appearance of light gives rise to the hyperpolarization originated by the closure of a certain number of canals, so that the sodium ions can not enter. The tension can in this way reach the order of -60 mV. The origin of the closure of the canals is believed to be due to the decrease of a complex called cyclic GMP, whose presence helps to maintain the canals open. The action of the light on the rhodopsin leads to, after a series of processes, the hydrolysis of the cGMP in such a way that this is no longer capable of maintaining the canals open. The hyperpolarization produced depends on the intensity of received light, but adjusting to the existing luminosity.

A highly significant fact is the internal amplification process produced. According to experimental evidence, one unique photon is capable of activating a certain rod. However, it is not evident is how one unique molecule of photopigment activating one unique ionic canal of the receptor can initiate the whole process, and moreover bearing in mind that the total number of them is between 10^8 and 10^9 . For this reason, it is believed that there is an intermediary cascade process, through a series of intermediary messengers, by which the amplification is achieved. The cones reach an equivalent effect after absorbing between 8 and 10 quanta of light.

1.5.1.3. Summary of architectures of visual processing in the retina of the vertebrates

The receptors possess two types of synapses with the bipolar cells. One of them, that involving the *flat bipolars*, is conventional in appearance and is found in the base of the receptor. On the contrary, there is another less usual synapses which takes place with the *invaginated bipolars* and also with a certain number of horizontal ones, constituting a kind of three-way junction. In this last case, the receptor acts on both types of cell and the action on the bipolars is, in a certain way, modulated by the horizontal ones. Given that the latter receive information from the receptors that cover a relatively wide area, it seems logical to think that the horizontal ones give rise to a certain *lateral inhibition* mechanism.

Although the electrical responses of both cells are very similar to those of the receptors, in terms of scale of values and times, there are two very significant differences. The first is that there are two functional types of bipolar cells. One of them depolarises as a response to the signal transmitted by the receptor while the other hyperpolarizes. Besides this fact, due to the presence of the horizontal ones, the properties of the reception field are quite different to the cones and rods. While in the case of the receptors it is reasonably simple, since the hyperpolarization is caused by a relatively small area, in the case of the bipolars the field is larger and non-uniform. The light which falls in the centre has a different effect to the light which falls peripherally. Thus, a cell depolarises when a bright spot shines on the centre of its receptive field and hyperpolarizes when the focus is on the surroundings and viceversa. This means that bipolars respond more strongly to small stimuli centred in their field than to those spread between the centre and the periphery. Thanks to this, objects can be detected which are brighter or darker than their surroundings.

Finally, it should be stated that in some cases the horizontal cells can also carry out a small feedback action on the receptors which have not received a signal. With this, the information can be shared among a set of them which can favour a type of averaging out over large areas of the retina, to try to distinguish very weak stimuli immersed in a certain ambient light. In some cases direct synapses can even be observed among various receptors. In the zones distant from the fovea, the two previous facts are usually quite common, so the number of nerve fibre terminals can be much less than that of cones and rods. On the contrary, in the fovea, most of the bipolars connect directly to a unique cone or rod. With this sharpness is increased at the expense of sensitivity.

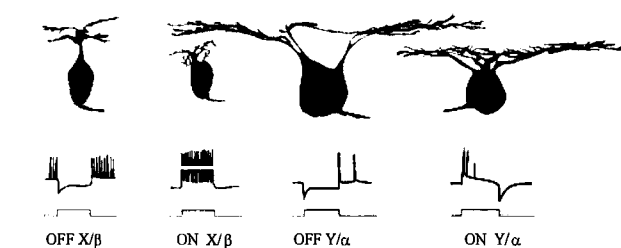
The next set of cells which merit special attention are the amacrine and the ganglionic cells. Their principal difference, compared to the last ones, is that their response to light is a series of short lived pulses rather than a constant tension. In the same way as the dipolar cells, the ganglion cells have, in the majority of the cases, some receptive fields

made up of a central region surrounded by an antagonistic type environment. Besides, nearly all of them have the additional property that they respond only in a transitory way when the retina changes abruptly from one level to another. In some cases, a transitory series of impulses appears when the light decreases ("off" response) or increases ("on" response). On other occasions these pulses appear at the beginning and end of a period of constant illumination ("on-off" response). A cell with an "on" response in its centre normally shows an "off" response in its surroundings and viceversa (Figure 1.8), while it has "on-off" responses in intermediary regions.

Thus, with respect to the properties of the receptor field, the ganglion cells are very similar to the bipolar ones. The only additional element appearing, the transitory response one, may be the result of the feedback inhibition due to the amacrine, whose response is, in turn, very similar to that of the ganglion ones. The set of connections capable of carrying out autoinhibition and lateral connection tasks is thought to be the cause of the temporary response of the ganglion cells.

It should be indicated that the amacrine appear in a large number of forms and types, each one of which has a differing morphology and, in many cases, its own type of synaptic transmitter. It seems possible that each one of these types has a specific function, but there still is not a lot of data about this.

Among the ganglion cells there is a small number which have constant responses. It seems that these supply information to the brain about the level of ambient light intensity so it



GANGLION CELLS IN THE CAT RETINA

β CELLS GIVE SUSTAINED RESPONSES TO LIGHT. CONDUCT RELATIVELY SLOWLY

α CELLS HAVE LARGER RECEPTIVE FIELDS AND GIVE TRANSIENT RESPONSES TO LIGHT

OFF-CENTRE CELLS FORM SYNAPSES IN THE OUTER PART OF THE INNER PLEXIFORM LAYER

ON-CENTRE CELLS FORM THEM IN THE INNER PART

β CELLS DO NOT RESPOND WELL TO QUICKLY MOVING STIMULI

α CELLS CONDUCT RELATIVELY QUICKLY. SHOW A BRISK RESPONSE TO THE ONSET OF THE STIMULUS BUT QUICKLY CEASE RESPONDING TO A CONTINUOUS STIMULUS. RESPOND WELL TO MOVING STIMULI.

Fig. 1.8. Ganglion cells in the cat retina.

can make some interpretations of images. In fact, there is a very large number of functional classes of ganglion cells. Most of them are related to their size and the form of their dendritic tree. The most general classification divides them in type Y cells and type X cells. The former are big, with high conduction velocities and very abrupt responses to movement or changes in light. The latter, X type, are much more numerous, smaller and slower, having uninterrupted responses when different parts of their receptive fields are illuminated simultaneously. Some of these differences seem to be related to the path by which the excitation reaches them. If it mainly

comes from the bipolars, a maintained response is produced, while if it comes from the amacrine, it is transitory. Another type of cell has also been described, the W, which has much more complex although slower responses. In total there are more than 23 types of different classes of ganglion cells in the relevant literature, although some of them do not appear in all types of mammal.

According to what has been seen up to now, the possibilities of configuring a model of the retina are very complicated, if the aim is to encompass all the functions which it carries out. On the other hand, if the only objective, in a first approach, is to simulate the behaviour of some of its neurons, relating amongst themselves only a limited number of them, the result could be positive without too many complications. This model, which might be very simple, could in turn serve as a basis in order to pass to higher levels of simulation.

There are numerous models of elemental character in the relevant literature. One of the most significant of them all was presented by Dowling in 1970. It describes a simple scheme composed of only two photoreceptors whose outputs act on the corresponding bipolar cells, joined, in the habitual way, by only one horizontal cell. The extremities of the bipolar cells, joined by an amacrine, feed three ganglion cells, two of which are connected directly to the dendrites of the corresponding bipolar cell and the third to dendrites of the amacrine. Each one of these ganglions gives rise to a different type of action potential, which correspond to those supplied by the ganglions type OFF X/beta, ON X/beta and a mixture of the OFF Y/alpha and ON Y/alpha. A scheme of this model is shown in Figure 1.9. A simulation of the model has been developed using techniques derived from structures used in Optical Computation [7]-[14].

Much more complete schemes than the previous one which now have different types of amacrine, like 5-HT and A2, in which the

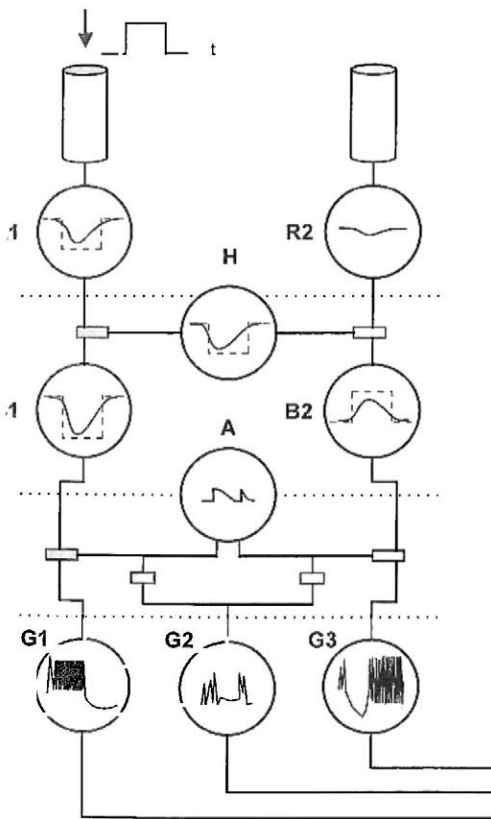


Fig. 1.9. Dowling scheme of the mammalian retina and cells response to light stimulus.

two possible types of synapses, inhibitory and excitatory, are made to intervene, have been developed since then. One of the most characteristic is the one shown by R.A. Barker which appears in Figure 1.10.

This model, in contrast to Dowling's, has only two ganglion cells as exits, and so its application to complex functions is also quite limited, although it does give some different possibilities to the previous model.

1.5.1.1.4. Signal Processing in the Visual Cortex [15]-[17].

The retina, despite its complexity, can be considered as one of the better known parts of the human body, however the same is not true of the cerebral cortex. This is where the most complex processing of the received signal takes place and, in fact, where the superior phase of knowledge is arrived at. For this reason, this region will be treated in much less detail than the retina. Besides knowing much less about it than the retina, going into depth about the behaviour would require much more space than is available. Only some brief ideas about its global behaviour and certain details about its parts will be given.

The first thing it is necessary to return to is the strategy which will be adopted here, to solve the problem of vision. There are two possible approaches which can be taken. A first, purely phenomenological, is to determine the functions carried out by the vertebrate visual system and, using the available technology, to try to configure an artificial system which behaves like the natural one. This is the most commonly adopted approach, for instance, in the field of artificial vision in Robotics. The second, on the contrary, is to try to understand the function of the visual system, model it, and finally attempt to configure an artificial system which resembles it as much as possible in terms of behaviour and methodology. This second approach, although it may offer equivalent final results to the first, has the

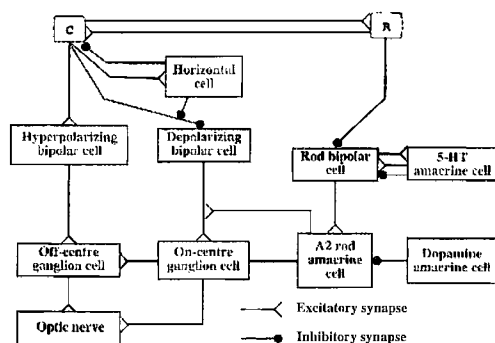


Fig. 1.10. Barker schematic summary of synaptic connections in mammalian retina.

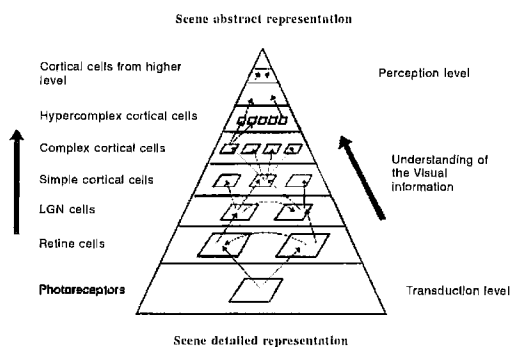


Fig. 1.11. The parallel-hierarchical architecture of the human visual pathway, from the retina (transducer level) to the visual cortex (perception level)

SIGNAL-SYMBOL PARADIGM OF A MACHINE AS A VISION SYSTEM

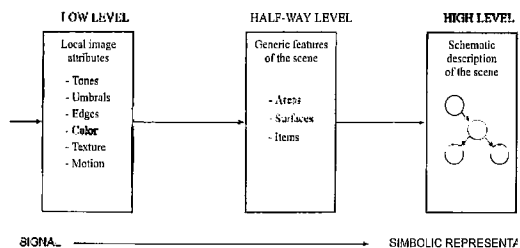


Fig. 1.12. The basic analytical levels of the signal-to-symbols paradigm for a machine vision system.

advantage that it is of interest not only to Engineering but also to Neurophysiology. In fact, we can consider it to be a Neurobiological approach. The latter approach will be adopted here.

Derived from the above, the first step to be made is to determine the way living beings establish the abstract representation of a visual image. In Figure 1.11, the form of establishing this representation is shown, according to M.M. Gupta and G.K. Knopf [18].

As can be seen, starting from the photoreceptor cells, it goes up the levels of abstraction progressively through the rest of the cells of the retina, from the *lateral geniculate nucleus*, LGN, reaching the simple cortical cells, then the complex ones, the hypercomplex and finally the high level cortical cells. This series of steps gradually changes the information from a pure signal transduction, in the first layers, to an understanding of this information, and lastly to the final perception. The triangular or pyramidal form shown in the Figure is, in fact, the real form in living beings. Although the number of photoreceptors is large, as one advances in the visual representation, the number of cells gradually becomes smaller until it is reduced to a much smaller magnitude than at the initiation. As has been represented in the same figure, in the last layers, appearing in white, the mechanisms and functions carried out there are still beyond our knowledge.

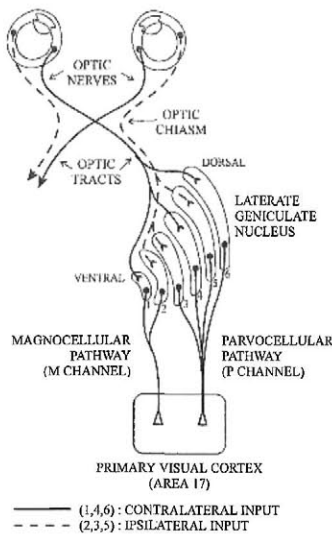


Fig. 1.13. Inputs from the right hemiretina of each eye to the different layers of the right geniculate nucleus. They create a complete representation of the left visual hemifield.

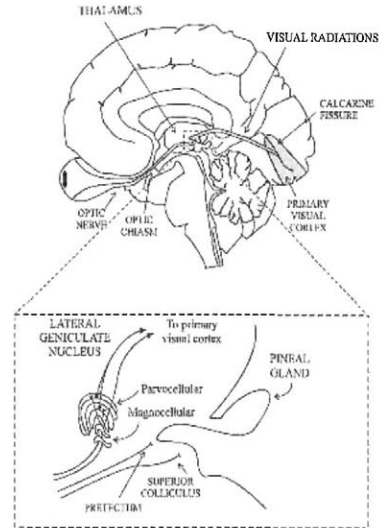


Fig. 1.14. Simplified diagram of the projections from retina to the various visual areas of the thalamus (lateral geniculate nucleus), midbrain and area 17 of the cerebral cortex.

In Figure 1.12, a more schematic representation of the above is shown, in which the Signal-Symbol paradigm which takes place in the visual system appears divided into three levels: the first of detection of specific details of the scene, like edges, textures or movement; an intermediary one, where the generic attributes of the system are captured, like wider regions, surfaces or objects; and finally, a higher level where the scene is detected as an entity. That is, we have passed from a signal composed of more or less unconnected parts to a symbolic representation.

The specific way in which the above takes place in the brain can be seen in Figures 1.13 and 1.14. The optic nerves, derived from the ganglion cells of the retina, emerge from each ocular globe by two completely different paths.

Those coming from the nasal part, after crossing in the optic chiasm, arrive at the opposite region in the brain, of the LGN, situat-

ed in the thalamus. That is, the signal of the right eye constitutes the contralateral entrance to the zones 1, 4 and 6 of the LGN situated in the left part of the thalamus. Something analogous happens with the signal from the left eye. The signals collected in the lateral part of each ocular globe, also reach the optic chiasm, but do not cross paths instead constituting the ipsilateral entrances to the regions 2, 3 and 5 of the LGN situated in the same part of the thalamus.

The LGN constitutes a form of relay station of the signals going to the brain, although no recognition or signal processes take place there. In fact, the brain itself sends signals to the thalamus which indicate whether the sensorial centres should or should not continue to the cortex. For example, in the case that the living being is asleep, the acoustic signals coming from the ear are blocked in the thalamus and do not proceed to the auditory centre of the cortex. This blocking is governed by the brain itself which indicates that it is in a state of repose.

Two different paths go out of the LGN: the magnocellular from regions 1 and 2, and the parvocellular from 3, 4, 5 and 6. These paths also receive the names M and P, respectively. As their names indicate, the magnocellular path is derived from the bigger ganglion cells, while the parvocellular comes from the smaller ones. As a consequence of this, the first has information about large surfaces, while the parvo has information about smaller areas and so, can recognise greater detail. Both paths go directly to the primary region of the visual cortex, specifically, to area 17, or V1, according to the technical terminology. From here, the signal advances through the different areas of the superior levels of the cortex, following the simplified scheme of the cortex of the monkey, as shown in Figure 1.15.

A more detailed scheme of these paths appears in Figure 1.16.

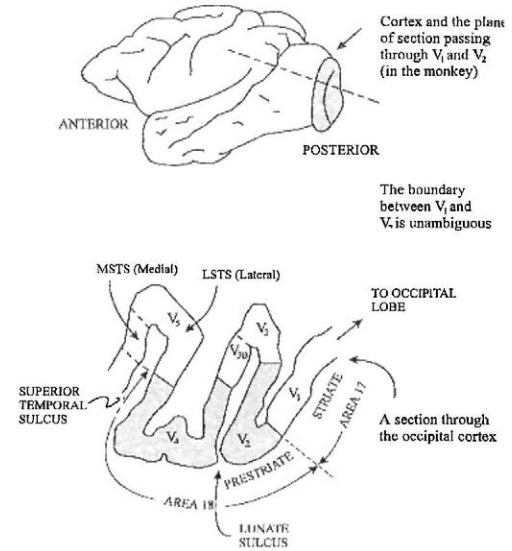


Fig. 1.15. Relation of the primary visual cortex V_1 to V_2 , V_3 , V_4 and V_5 in the monkey. (a) The cortex and the plane of section passing through V_1 and V_2 . The boundary between V_1 and V_2 is unambiguous. (b) A section through the occipital cortex.

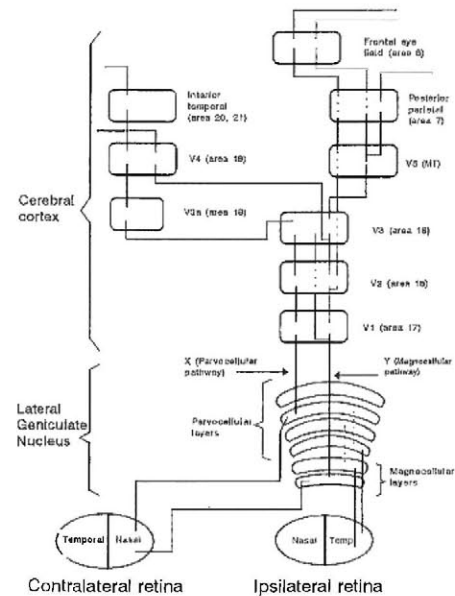


Fig. 1.16. Visual projection from X and Y cells in the retina to the various visual areas of the cerebral cortex in the monkey.

Without going into great detail of the previous paths and levels, we are going to comment briefly on some of the characteristics determined by the evolution towards higher levels. In the visual system, like in most of the rest of the animal systems, the passage from one level to another is carried out by integration of the captured signals or processing in the precedent ones. Figure 1.17 shows two specific cases of receptive fields of neurons of second order.

In the first, in which there is only a receptive field, it can be seen that the signal processed by a neuron of this type is the result of summing those coming from the first order ones. If each one of them includes a determined surface, its set constitutes the receptive field of the neuron of superior order, and so, the surface it can analyse is the sum of the previous ones. In the second case, as well as the previous excitation region, a new environment must be added which is covered with neurons that, through other inhibitors, is capable of neutralising the signal captured by the central part of the receptive field. Due to this fact, for example, if there is light in the central zone, the secondary neuron can generate an action potential, while, on the contrary, if the light covers the whole surface, the inhibitory part cancels the excitatory and the secondary neuron generates no signal at all. This is the reason for the difference in behaviour of a large number of cells which, depending on the form or surface of the illuminated zone, can generate one type of signal or another.

Another example of the way in which the cortex works is related to the way the different orientations of a slit of light or a line im-

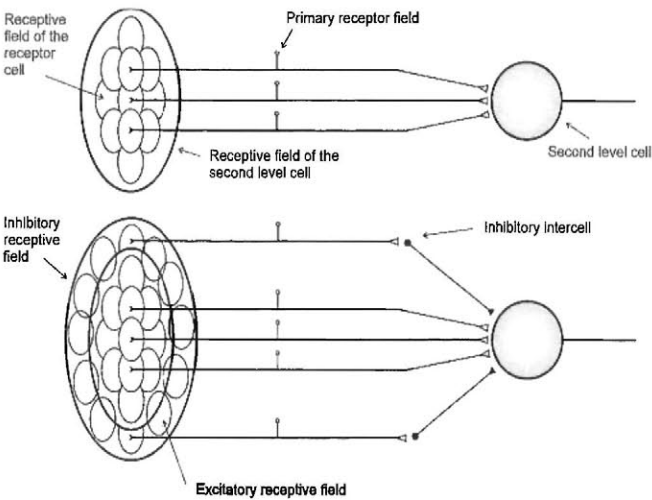


Fig. 1.17. Receptive field structure. (a) Many peripheral receptors converge onto a single sensory neuron in the central nervous system. As a consequence, the receptive field for a central neuron is much larger. (b) The receptive field of a central sensory neuron may have a central excitatory receptive field surrounded by an inhibitory region.

peding the passage of light are detected. The way to achieve this is thanks to the structure of the primary visual cortex. As can be seen in Figure 1.18, this is divided in a series of slabs each one of which has very differentiated properties.

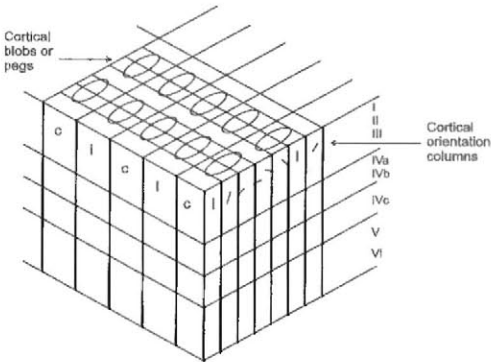


Fig. 1.18. Highly stylized representation of a slab of visual cortex, showing its organization into columns, narrow strips in which cells share a common preferred orientation.

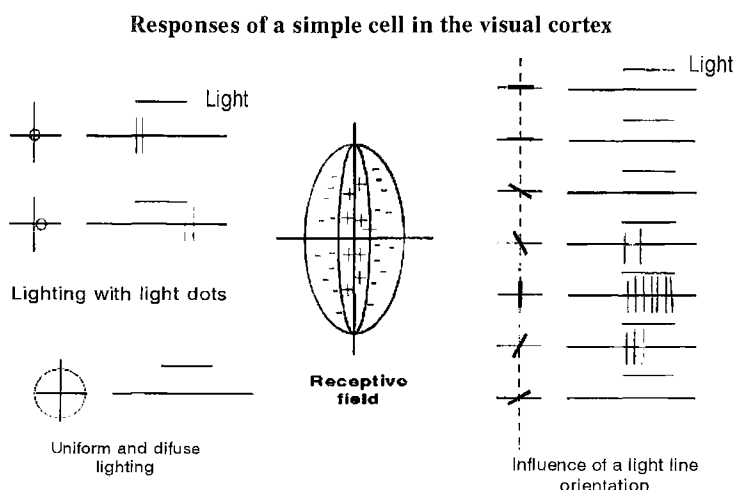


Fig 1.19. Responses of a simple cell in the visual cortex.

In one direction it can be seen that the signals they analyse come from the contralateral and ipsilateral paths mentioned previously. Their size is approximately 1 mm. In the other direction, the configuration of the receptive fields of each neuron is such that they can only generate signals when the incoming light is of a particular orientation. Every 50 micra, the favoured orientation turns through an angle of approximately 10° , thus with 5.4 cm any possible orientation can be recognised. The response mechanism of this type of cell to different types of luminous excitation appears in Figure 1.19.

The figure shows the neuronal responses to suitable excitations, diffuse illumination and lines of light, like those indicated. In an analogous way, in the same zone, colours can be recognised by some cylindrical shaped zones which appear in Figure 18. The details of this process can be seen in any Neurophysiology textbook.

1.6. Conclusions

Everything I have explained up to now is no more than the possible starting point for the surprising and fruitful paths that can be taken in the next few years. The only intention has been to show some examples of the possible approaches which could be adopted and to give some examples. As was mentioned in previous chapters, the path has still not been laid and many curious

people will have to wander it before it can be used without danger of becoming lost. The objective of this chapter has only been to stimulate the curiosity. If I have achieved this I will be more than satisfied.

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